



## IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

## Application

Inventor(s): Patrick P. Naulleau  
 SC/Serial No.: 09/981,500  
 Confirm. No.: 6932  
 Filed: October 16, 2001  
 Title: A HOLOGRAPHIC ILLUMINATOR  
 FOR SYNCHROTRON-BASED PROJECTION  
 LITHOGRAPHY SYSTEMS

PATENT APPLICATION

Art Unit: 2872  
 Examiner: Lavarias, Arnel C.

Customer No. 23910DECLARATION OF PATRICK P. NAULLEAU, Ph.D.

Commissioner for Patents  
 Washington, DC 20231

Sir:

I, Patrick P. Naulleau, declare that:

1. I am the inventor or the above-identified patent application. I have been informed by counsel that the pending claims have been rejected in part based on the prior art reference, namely, Suzuki, U.S. Patent Publication No. US2002/0018179 A1, published February 14, 2002 and filed June 15, 2001.
2. *conception prior to ref. date* Prior June 15, 2001, I had conceived the subject matter of the invention as defined by the pending claims. Attached hereto is a copy of the disclosure and record of the invention which I prepared and submitted to Patent Department at Lawrence Berkeley National Laboratory.
3. Also prior to June 15, 2001, I had demonstrated the feasibility of the claimed invention. Attached hereto is a memorandum which I prepared prior to June 15, 2001 documenting the work that I had done. All of the work was done at the Lawrence Berkeley National Laboratory located in Berkeley, California.
4. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under §1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Date: 1/23/03

P. Naulleau  
 Patrick P. Naulleau

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**LAWRENCE BERKELEY LABORATORY**

LBL File No.

C1B-1661

Date Received

Disclosure and Record of Invention

This invention was made in the course of or under prime contract No. DE-AC03-76SF00098 between the U.S. Department of Energy and the University of California. This Disclosure and Record of Invention is prepared for the Office of the Assistant General Counsel for Patents, U.S. Department of Energy.

Mail completed disclosure to LBL Patent Department, 90-1121

Telephone ext. 7058 if you have questions regarding this form.

Title of Invention: A synchrotron based illuminator for small-field EUV lithography studies using a holographic diffuser

Please list names of those who contributed to the inventive thought and to the final result of the invention. If a patent application is filed the Patent Department will make a legal determination of inventorship.

<u>Contributor(s): Full Name</u>	<u>Title/Position</u>	<u>Employer</u>	<u>Division</u>	<u>Phone No.</u>	<u>Mail Stop</u>
<u>Patrick P. Naulleau</u>	<u>Optical Scientist</u>	<u>LBNL</u>	<u>MSD</u>	<u>4529</u>	<u>2-400</u>

Contributor(s) Permanent Home Address(es):

<u>Name</u>	<u>Citizenship</u>	<u>Street Address</u>	<u>City, State, and Zip Code</u>
<u>Patrick Naulleau</u>	<u>USA</u>	<u>5239 Miles Ave, Apt. A</u>	<u>Oakland, CA, 94618</u>

**IMPORTANT** - Check the funding source for this invention & provide the information requested:

☐ DOE only ; B & R Code \_\_\_\_\_ (See Division office for appropriate B & R code)

DOE Program Mgr. \_\_\_\_\_

☐ Non DOE sponsor (including WFO)

Sponsor Name \_\_\_\_\_

☐ CRADA

Private Sector Participant

EUUV/LLC

☐ Subcontract

Subcontract No. \_\_\_\_\_

Contractor \_\_\_\_\_

☐ Other

Describe \_\_\_\_\_

LBL Account Number

8336-12

LBL Principal Investigator

David Attwood

From what source do you reasonably expect future or continuing funding?

Source

EUUV/LLC

Is this ☒ continuing funding or ☐ future funding?

☐ No future funding is currently expected.

Conception (Date, Place):

Earliest documentation of your invention: (please provide date and identify the document)

First Sketch or Drawing:

First Written Description: ~~XXXX~~, part of transparency presentation at the EUV All Hands Meeting at LLNL

Names of witnesses or others with knowledge of facts relating to conception:

Jeff Bokor

Keith Jackson

Phil Batson

Reduction to Practice:

Date first model completed:

Date of operation and testing:

Place of test:

Results of testing:

Witnesses or others with direct knowledge of test:

Important: WAS ANY PROPRIETARY MATERIAL FROM OUTSIDE YOUR LABORATORY USED TO DEVELOP YOUR INVENTION (e.g., software code, cell line, antibody, DNA fragments, or chemical compound)? If yes, please describe.

NO

## DESCRIPTION:

Background of the invention Please summarize:

- 1) Technical problems overcome to make the invention,
- 2) What your invention enables people to do that couldn't be done as well before,
- 3) How people currently address the problem your invention addresses.

EUV Lithography is an emerging technology in the microelectronics industry. It is one of the leading candidates for the fabrication of devices with feature sizes of 70 nm and smaller. Synchrotron radiation facilities provide a convenient source of EUV radiation for the development of this technology. Currently the coherence and high flux properties of synchrotron undulator radiation is being used for crucial at-wavelength interferometry and alignment of complex EUV lithography optics. These interferometry results can be used to predict imaging performance, however, the final performance metric must always be actual imaging. It would be greatly beneficial to enable imaging studies to be performed at the same location as is performed the interferometry. The problem is, however, that relevant imaging studies require the use of partially coherent light as opposed to the coherent illumination required for interferometry and provided by the undulator beamline. The invention presented here allows the effective coherence of an undulator beamline to be tailored to small-field imaging requirements.

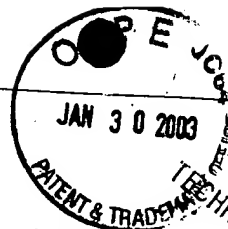
The use of an EUV diffuser has been proposed as the key element for destroying the beamline coherence. Such a device would be the EUV analog of conventional optical ground glass. The problem with this method, however, is that the EUV diffuser is extremely difficult to implement. It requires the fabrication of an engineered random relief substrate well controlled both laterally and in depth. Nearly atomic level accuracy is required in depth. The method presented here implements the EUV diffuser holographically. The diffusion characteristics are encoded into spatial modulations of a periodic spatial carrier. This alleviates the need to fabricate a well controlled multilevel substrate, reverting to the more conventional in-plane patterning situation. In addition to the holographic diffuser, the illuminator presented here employs a simple stationary low-cost spherical mirror.

Summary of the Invention Please include a sketch of the invention if possible (you may attach extra pages):

The goal of a lithographic illuminator is essentially to illuminate the reticle to be imaged with a range of angles. The partial coherence of the illumination ( $\sigma$ ) is the ratio of the illumination angular range to the numerical aperture of the imaging system. Additionally, each of the illumination angles must be comprised of light that is incoherent with the light at all other illumination angles. This condition is readily achieved by scattering a beam of coherent light with a moving diffuser. Scatter from the diffuser creates the requisite angles of illumination and motion of the diffuser guarantees the mutual incoherence of all these angles, assuming the observation (or exposure) time to be long relative to the speed of motion.

The major difficulty in fabricating an EUV diffuser for use in a non-critical-illumination system (a system in which the diffuser is not re-imaged to the reticle) lies in the control required of the scattering angle of the diffuser. Intrinsic roughness caused by the processing involved in creating the custom relief substrate, tends to increase the scattering angle significantly above the angle desired for typical EUV systems. Typical EUV systems have numerical apertures ranging from 0.1 to 0.3, assuming a conventional coherence factor of 0.7 and magnification of 4, the diffuser would ideally have a scattering angle of approximately 1 degree. Uncontrolled roughness in a diffuser will typically scatter light over an angle of 10 degrees, leading to a two-dimensional loss factor of about 100 due to area effects. An additional loss factor of approximately 10 or larger would also be expected due to loss of multilayer reflectivity. These losses would have a dramatic effect on the optical throughput of the system.

The potential high-angle scatter and multilayer reflectivity loss problems can be mitigated by using a holographic diffuser and achieving the diffusion through in-plane spatial modulation of a periodic carrier as opposed to surface profile control. In the simple case of an amplitude hologram, ideal silicon substrates could be used for the multilayer base, essentially eliminating the intrinsic roughness. Binary phase holograms could also be used improving the diffraction efficiency at the possible cost of higher intrinsic roughness. However, because the binary phase hologram would require fewer steps and a lower overall phase height as compared to a conventional EUV diffuser, the intrinsic roughness could likely be better controlled. Even further diffraction efficiency could be obtained through the use of blazed-phase gratings at the possible cost of further increased intrinsic roughness.



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The use of a holographic diffuser instead of a conventional diffuser imposes two new difficulties, however. The first difficulty is the presence of the zero order which must be eliminated prior to illumination of the reticle and the second is the increased spatial resolution demands on the lithography. The spatial carrier in the holographic diffuser has the effect of increasing the resolution requirements by, at least, a factor of 4. Both these limitations can be overcome by implementing a demagnifying spatial-filtering system after the diffuser. The spatial filter would eliminate the zero-order component of the holographic diffuser and the demagnifying system would relax the patterning-resolution requirements.

The demagnifying system is comprised of a simple spherical mirror used to re-image the diffuser to the reticle. The spatial filtering is provided by a stop placed between the diffuser and the spherical mirror that selects only the holographic order. Order separation is achieved in the stop plane by properly choosing the spatial-carrier frequency in the holographic diffuser and having the incoming illumination beam focused to the stop plane.

Because the demagnifying system reduction ratio has an inverse effect on numerical aperture, the numerical aperture required of the holographic diffuser is, in fact, smaller than the illumination numerical aperture sought at the reticle. This has the effect of relaxing the holographic diffuser fabrication resolution requirements.

As with any illuminator relying on a diffuser to destroy the coherence of a coherent beam, the holographic diffuser must be moved at rate fast relative to the observation (exposure) time in order for the desired coherence modification to be achieved. Without motion, the diffuser creates the requisite multiple angles of illumination, however, the light at each of these illumination angles remains mutually coherent as they are all derived for a single coherent beam. Incoherence requires both multiple angles of incidence and mutual incoherence of all these angles. This effect can be effectively achieved by rapid motion of the diffuser. In the case of the holographic diffuser, however, the diffuser cannot simply be rotated as is typically done with conventional diffusers because this would cause the carrier to rotate in space. Instead, the holographic diffuser must be translated in  $x$  and  $y$  only.

Figure 1 shows the configuration for this illuminator. Refer to the attached "Alternate illuminator for the SES using a holographic, diffusing M7" memo for further implantation details.

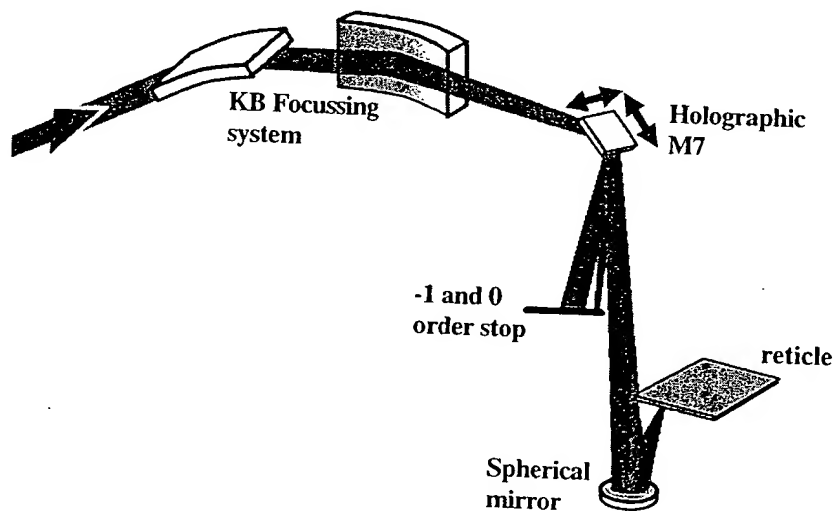


Fig. 1. EUV holographic diffuser illuminator design.

List uses of the invention - research, commercial, pilot plant, etc.; Think as broadly as possible.  
Identify companies that might be interested in licensing this technology.

Illumination systems for devices requiring incoherent illumination. EUV microscopy. EUV lithography. EUV coherence tomography.

Publications (including LBL reports, meeting abstracts, or prior patents or patent applications) that ACTUALLY DESCRIBE or RELATE to the invention:

<u>Title/Subject</u>	<u>Publication</u> <u>Date</u>	<u>Indicate "Describes"</u> <u>or "Relates" to Inv.</u>	<u>Journal and/or LBL Rep. No.</u> <u>If prior LBL pat. appl., IB#</u>
An alternate illuminator for the SES using a holographic, diffusing M7	<del>1994</del>	<u>Describes</u>	<u>CXRO internal memo</u>

Papers you have SUBMITTED or are PREPARING for publication that describe or relate to your invention:

<u>Title/Subject</u>	<u>Anticipated</u> <u>Publ. Date</u>	<u>Indicate "Describes"</u> <u>or "Relates" to Inv.</u>	<u>Journal and/or LBL Rep. No.</u> <u>If prior LBL pat. appl., IB#</u>
_____	_____	_____	_____

Please notify the Patent Dept. (x7058) if you later plan new publications that describe or relate to the invention.

I believe myself to have contributed to be the above-described invention. (Each contributor must sign.)

CONTRIBUTOR: _____	DATE: _____
WITNESS: _____	DATE: _____
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Read and Understood by:

\_\_\_\_\_  
LBL Patent Department Reviewer

Date: \_\_\_\_\_

# MEMO



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MATERIALS SCIENCES DIVISION  
CENTER FOR X-RAY OPTICS

TECHNOLOGY CENTER 2800

To: Keith Jackson  
From: Patrick Naulleau  
CC: Phil Batson, Seno Rekawa, Ken Goldberg, and Jeff Bokor  
Date: ~~DATE~~  
Re: Alternate illuminator for the SES using a holographic, diffusing M7

The success of the Subfield Exposure Station for static printing with ETS optics at the ALS as currently envisioned relies heavily on the development of an EUV diffuser<sup>1,2</sup> to be used as the crucial component of the illuminator. The diffuser approach has several advantages, including its simplicity and flexibility in terms of optical design, and its mechanical simplicity and small space requirements. The difficulties involved in the actual fabrication of the diffuser, however, make it a rather high-risk approach. To mitigate risk to the overall project, alternative "backup" illuminators have been designed. Here we describe one of these illuminators.

The major difficulty in fabricating the EUV diffuser for use in a non-critical-illumination system lies in the control required of the scattering angle of the diffuser. Intrinsic roughness caused by the processing involved in creating the custom relief substrate, increases the scattering angle significantly above the desired 1 to 2 degree half-angle scatter. This in turn has a dramatic effect on the optical throughput of the system.

The potential high-angle scatter problem can be mitigated by using a holographic diffuser and achieving the diffusion through in-plane spatial modulation of a periodic carrier as opposed to surface profile control. In the simple case of an amplitude hologram, ideal silicon substrates could be used for the multilayer base, essentially eliminating the intrinsic roughness. Binary phase holograms could also be used, improving the diffraction efficiency at the possible cost of higher intrinsic roughness. However, because the binary phase hologram would require fewer steps and a lower overall phase height as compared to the diffusers described earlier,<sup>1,2</sup> the intrinsic roughness could likely be better controlled. Even further diffraction efficiency could be obtained through the use of blazed-phase gratings.

The problem with the holographic diffuser is that elimination of the zero order and extremely high-resolution spatial patterning is required. The spatial carrier increases the resolution requirements by, at least, a factor of 4. These limitations can be overcome by implementing a demagnifying spatial-filtering system after the diffuser. The spatial filter would eliminate the zero-order component of the hologram and the demagnifying system would relax the patterning-resolution requirements.

The current design for the diffuser-based illuminator does not easily accommodate an additional imaging system between the diffuser and the reticle, therefore the diffuser would have to be located earlier in the optical path. A convenient location is on the M7 turning mirror currently used to redirect the undulator beam into the interferometer at the proper angle. As with the mechanical M7 illuminator design described elsewhere,<sup>3</sup> a spherical mirror can be positioned below the reticle stage to re-image M7 (which in this case incorporates the holographic diffuser) to the reticle. The spatial filtering of the zero order is achieved through free-space propagation, a stop, and a spatial carrier of adequately high

frequency in the hologram. Order separation at the stop can be further guaranteed by forcing the incoming beamline illumination to focus to the stop plane. In this case the zero-order of the holographic diffuser, which is essentially an unmodified version of the illumination beam, will be as small as possible in the stop plane.

It should be noted that unlike the non-critical diffuser-based illuminator, this system does not allow for *in situ* control of the coherence.

Figure 1 shows the configuration for the holographic illuminator described here. The imaging mirror is placed in the same position as would be the conventional diffuser (100 mm below is the object plane). The holographic diffuser is incorporated into the M7 mirror positioned approximately 237 mm above the object plane. This configuration yields a reduction ratio of 3.34 from the holographic diffuser to the reticle.

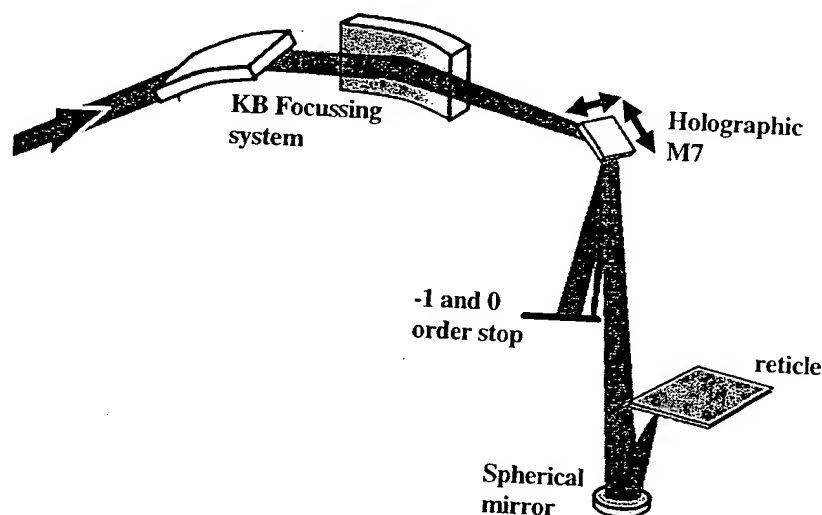


Fig. 1. Schematic of the holographic diffusing M7 critical illuminator alternative for the SES.

Because the reduction ratio has an inverse effect on numerical aperture (NA), the NA required of the holographic diffuser is 3.34 times smaller than the illumination NA sought at the reticle. To achieve a  $\sigma$  of 0.7 with the ETS optic (object-side NA = 0.025), the required holographic diffuser NA is  $(0.7)(0.025)/3.34 = 0.0052$ . This condition significantly relaxes the holographic diffuser fabrication requirements. Figure 2 shows the one-dimensional, single-sided spectrum of the holographic diffuser in the direction of the carrier. The carrier frequency ( $\theta_c$ ) should be chosen such that separation is achieved between the diffracted order and the zero order. Noting that the zero order is in general twice as wide as the diffracted order, the carrier frequency should be at least 1.5 times larger than the NA desired from the holographic diffuser. Additionally, in order to facilitate the selection of the diffracted order by way

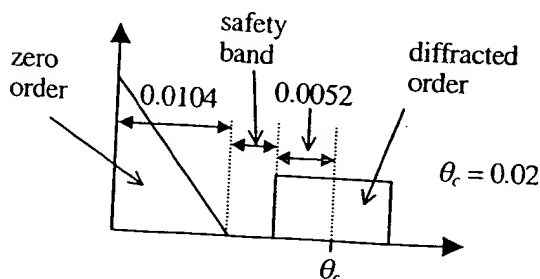


Fig. 2. Single-sided, one-dimensional spatial frequency spectrum of a typical holographic diffuser in the direction of the carrier.



of a spatial filter, an extra safety band should be added (Fig. 2). Choosing a safety band approximately equal to the desired NA sets the carrier frequency (angle) to 0.02 rad (1.15°). This corresponds to a holographic carrier period of 670 nm. To achieve the desired NA from the diffuser requires the carrier to be modulated at a resolution of approximately 250 nm. These specifications are well within the capabilities of current lithography tools including the CXRO *Nanowriter*.

It is also important that the imaging mirror itself not limit the illumination NA. Given the position of the imaging mirror, its diameter is simply required to be larger than 5 mm to satisfy this condition. Because the spherical imaging mirror is a condenser mirror, the wavefront specifications can be rather loose. The required specifications for this case are identical to those described for the scanning-angle M7 illuminator.<sup>3</sup>

As with any illuminator relying on a diffuser to destroy the coherence of a normally coherent beam, the holographic diffuser must be moved at rate fast relative to the observation (exposure) time in order for the desired coherence modification to be achieved. Without motion, the diffuser creates the requisite multiple angles of illumination, however, the light at each of these illumination angles remains mutually coherent as they are all derived for a single coherent beam. Incoherence requires both multiple angles of incidence and mutual incoherence of all these angles. This effect can be effectively achieved by rapid motion of the diffuser. In the case of the holographic diffuser, however, the diffuser cannot simply be rotated as this would cause the carrier to rotate in space. Instead, the diffuser must be translated in x and y only.

As with the scanning-angle M7 illuminator,<sup>3</sup> the system described here is a critical illuminator. Care must be taken to avoid non-uniformities at the diffuser from being transferred to the illumination of the reticle.

We note that we have previously rejected the idea of using naturally rough diffusers for the non-critical illuminator<sup>2</sup> due to the uncontrollably large scatter angle greatly reducing the optical throughput of the system. This is caused by illuminating a much larger portion of the reticle than is in fact desired in addition to the induced multilayer reflectivity loss. In principle, a critical system like the one described here could be used to mitigate this problem. The obvious choice would be to replace the M7 mirror with a naturally rough diffuser. Such a diffuser, however, would have a scatter half angle of approximately 10° and would require a 116-mm diameter condenser lens to achieve the desired throughput gains in the SES configuration. Such a large diameter condenser would not be mechanically compatible with the current system, and furthermore the additional NA would not be accepted by the ETS optic thereby negating the collection gain of the condenser. Also, the roughness induced multilayer reflectivity loss is not addressed by the condenser solution. The method could be feasible, however, assuming a complete redesign of the illumination-system light path and that the roughness-induced multilayer loss is tolerable.

## References

1. P. Naulleau, "Modeling of EUV diffusers compatible with electron-beam lithography fabrication methods," [REDACTED]
2. P. Naulleau, "EUV diffusers for synchrotron-based imaging experiments," [REDACTED]
3. P. Naulleau, "An alternate illuminator for the SES," [REDACTED]



MATERIALS SCIENCES DIVISION  
CENTER FOR X-RAY OPTICS

## MEMO

To: Keith Jackson  
From: Patrick Naulleau and Erik Anderson  
CC:  
Date: [REDACTED]  
Re: Visible-light, proof-of-principle implementation of the generalized-fill holographic illuminator

The development of the Subfield Exposure Station (SES) for static printing with ETS optics at the EUV interferometry beamline has led to the design of various decoherentizing small-field illuminators including a holographic illuminator capable of producing a generalized fill pattern.<sup>1,2</sup> This illuminator uses a holographic optical element (HOE) to serve as the new effective illumination source.

In general, an HOE can be designed to generate any arbitrary far-field diffraction pattern. When such an element is used as the source in a critical illumination system (Fig. 1), any arbitrary pupil-fill pattern can be synthesized. In this case, the reticle-plane illumination pattern is set by the HOE-plane illumination pattern.

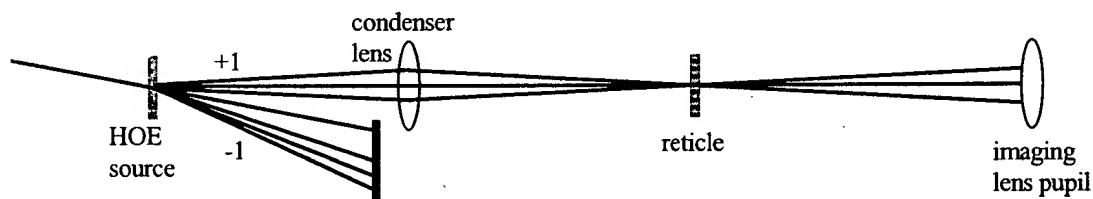


Fig. 1. Critical illuminator using an HOE-synthesized source.

The HOE could be a transmission device as depicted in Fig. 1, or a reflection device. The reflection implementation is attractive for EUV applications because it allows the HOE to be integrated into an existing optical component, thus, simplifying the system design and optimizing throughput. Figure 2 shows such an implementation for the SES (this configuration is described in detail in Refs. 1 and 2).

As described previously,<sup>2</sup> the EUV implementation of the HOE is ideally a phase-only device and is, furthermore, preferably realized using a binary-phase carrier. The HOE pattern required to

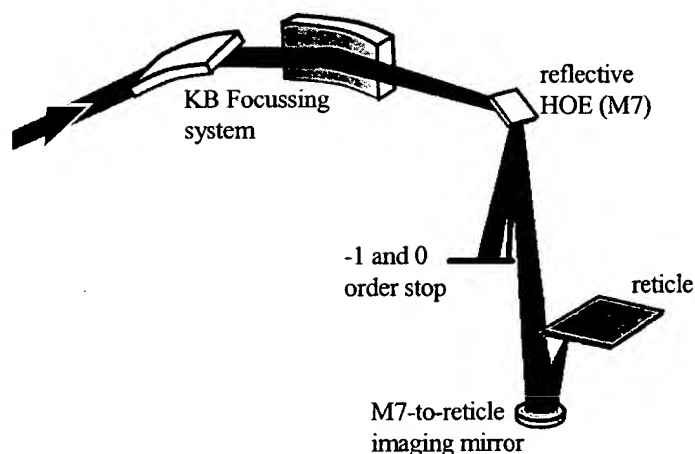
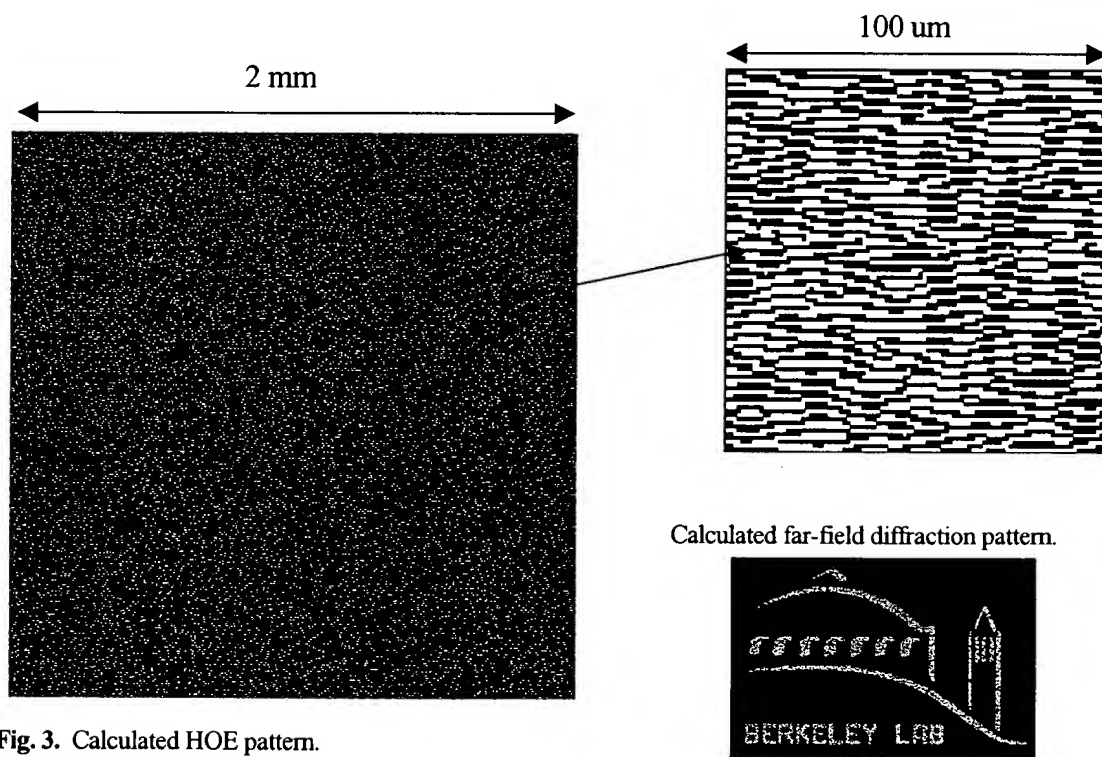


Fig. 2. SES implementation of HOE-synthesized source critical illuminator.

generate any arbitrary fill pattern under this restrictive condition can be computed by way of iterative phase-retrieval techniques.<sup>2,4</sup>

The feasibility of implementing such a device at EUV has been demonstrated by fabricating a visible-light analog. The off-axis, pure-phase HOE has been designed to generate the LBL logo using the iterative phase-retrieval method. The binary-phase carrier is created by producing a two-level relief pattern onto a silicon wafer. The device is rendered uniformly reflective at visible light by aluminum plating. To create an EUV device, the aluminum coating would simply be replaced by an appropriate reflective multilayer coating. The lithographic patterning was done using the CXRO *Nanowriter* electron-beam lithography tool.

Figure 3 shows the calculated HOE pattern used as the basis for the *Nanowriter* patterning along with the corresponding calculated far-field diffraction pattern.. The HOE pattern is 2048×2048 pixels and covers at total area of 4 mm<sup>2</sup>. The HOE is designed to work at a wavelength of 633 nm and 20 degrees off normal. Accordingly, the binary pattern height is 168 nm. The black regions correspond to locations that are 168 nm taller than the white portions.



**Fig. 3.** Calculated HOE pattern.

Figure 4 shows the actual fabricated HOE wafer; 5 identical HOEs have been patterned near the center of the wafer. Also shown are two orders (the desired pattern and its complex conjugate) of the HOE diffraction pattern under He-Ne illumination.

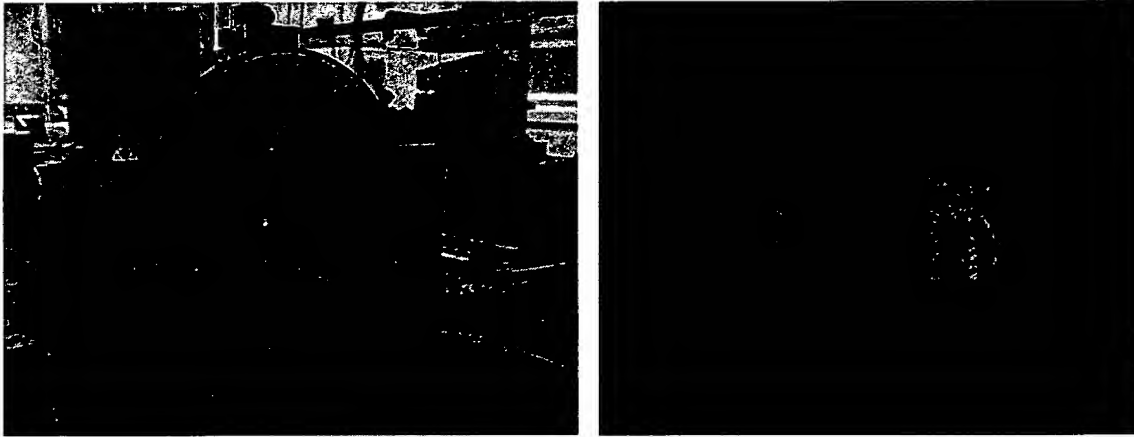


Fig. 4. Fabricated visible-light phase only off-axis HOE with binary phase carrier and its measured diffraction pattern.

This visible-light implementation demonstrates that using relatively simple binary height fabrication methods, we have the ability to produce HOEs with arbitrary diffraction patterns. Applying this to EUV would provide the basis for an arbitrary-fill illuminator. Completely redefining the fill would simply require changing one flat reflective optical element. We note that the *Nanowriter* used in this demonstration has ample resolution for the EUV implementation as well.

#### References

1. P. Naulleau, "Alternate illuminator for the SES using a holographic, diffusing M7," ~~XXXXXXXXXX~~
2. P. Naulleau, "Generalization of the EUV holographic-diffuser SES illuminator, Rev 1," ~~XXXXXXXXXX~~
3. R. Gerchberg and W. Saxon, "A practical algorithm for the determination of phase from image and diffraction plane pictures," *Optik*, **35**, 237-246 (1972).
4. J. Fienup, "Reconstruction of an object from the modulus of its Fourier transform," *Opt. Lett.*, **3**, 27-29 (1978).